PB83-202069

Fate of Coal Nitrogen during Combustion

Energy and Environmental Research Corp.
Irvine, CA

Prepared for

Industrial Environmental Research Lab.
Research Triangle Park, NC

1982

U.S. Department of Commerce
National Technical Information Service
NTIS

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before complet

1. REPORT NO.	2.	3.
EPA-600/J-82-314	JOURNAL ARTICLE	PB83-202069

4. TITLE AND SUBTITLE	5. REPORT DATE
Fate of Coal Nitrogen During Combustion	1982
	6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S)	8. PERFORMING ORGANIZATION REPORT NO.
S. Chen, M. Heap, and D. Pershing (Energy and Environmental Rsrch Corp.), and G. B. Martin (EPA)	

9. PERFORMING ORGANIZATION NAME AND ADDRESS	10. PROGRAM ELEMENT NO.
Energy and Environmental Research Corp. 18 Mason Irvine, California 92714	11. CONTRACT/GRANT NO. 68-02-2667

12. SPONSORING AGENCY NAME AND ADDRESS	13. TYPE OF REPORT AND PERIOD COVERED
EPA, Office of Research and Development Industrial Environmental Research Laboratory Research Triangle Park, NC 27711	Journal Article; 10/81 14. SPONSORING AGENCY CODE EPA/600/13

15. SUPPLEMENTARY NOTES IERL-RTP author Martin's Mail Drop is 62; his phone is 919/541-7504. Article was published in Fuel, Vol. 61, December 1982, pp 1218-1224.

16. ABSTRACT The paper describes the burning of 21 coals, covering all ranks and under a wide variety of conditions, to ascertain the impact of coal properties on the fate of fuel nitrogen. Fuel NC was identified by using a nitrogen-free oxidant consisting of Ar/C2/CO2. It was found that fuel NO formation depends on the reactivity of volatile nitrogen as well as on total nitrogen content. Internal species concentrations were measured under fuel-rich conditions, and it was found that: (1) the partition of nitrogen between NO, NH3, and HCN was dependent on coal type; and (2) total gas-phase nitrogen species (fuel rich) correlated with exhaust NO (fuel lean). This work will help in the generalization of low NOx burner technology to a wide range of fuels.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Pollution	Pollution Control	13B
Coal	Stationary Sources	21D
Nitrogen	Fuel Nitrogen	07B
Combustion		21B

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS (This Report)	21. NO. OF PAGES
Release to Public	Unclassified	9
	20. SECURITY CLASS (This page)	22. PRICE
	Unclassified	

EPA Form 2220-1 (9-73)

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

EPA-600/J-82-314
JOURNAL ARTICLE

Fate of coal nitrogen during combustion

S. L. Chen, M. P. Heap, D. W. Pershing and G. B. Martin*
Energy and Environmental Research Corporation, 18 Mason, Irvine, California 92714, USA
* *Industrial Environmental Research Laboratory, US Environmental Protection Agency, Research Triangle Park, North Carolina 27711, USA*
(*Received* 12 *July* 1982)

A total of 21 coals covering all ranks have been burned under a wide variety of conditions to ascertain the impact of coal properties on the fate of fuel nitrogen. Fuel NO was identified with a nitrogen-free oxidant consisting of Ar–O_2–CO_2. In general, under fuel-lean conditions fuel NO formation increases with increasing fuel nitrogen content; however, other fuel properties also significantly affect the fate of fuel-bound nitrogen during combustion. In particular, fuel nitrogen conversion appears to be greater with coals containing a high fraction of volatile reactive nitrogen. Under fuel-rich conditions measurements of first-stage and exhaust-species concentrations suggest that the optimum stoichiometry for minimum emissions is a function of fuel composition. As first-stage stoichiometry is decreased, the NO formed in the first stage decreases, but other oxidizable gas nitrogen species increase as does nitrogen retention in the char. Total fixed nitrogen generally increases with increasing fuel nitrogen and correlates well with excess air exhaust emissions. The distribution of the total fixed nitrogen species leaving the first stage is strongly dependent upon the coal composition. Of the 12 coals tested in detail, only 1 (the high-volatile B bituminous from Utah) produced high HCN concentrations. The low-volatile Pennsylvania anthracite formed almost no HCN or NH_3 even under extremely fuel-rich conditions. In general, the first stage NO percentage decreased significantly with decreasing coal rank from anthracite to lignite. Conversely, the relative importance of NH_3 grew with decreasing rank. HCN was greater than NH_3 in all bituminous tests, but less than NH_3 with all subbituminous and lignite coals.

(Keywords: coal; nitrogen; combustion)

The development of NO control strategies for coal-fired boilers has received considerable attention over the past decade. It was established in pilot-scale studies[1] that fuel–air mixing controlled by burner design affected the formation of NO in pulverized coal flames and that rapid mixing of coal volatiles and air promoted NO formation. In bench-scale and research studies the significance of fuel nitrogen oxidation[2], the factors controlling fuel nitrogen evolution[3,4], and the conditions that affect NO formation from pulverized coal under fuel-rich conditions[5,6] were established. Burner designs that are capable of minimizing emissions from field-operating boilers[7–9] have been demonstrated at various scales and more advanced combustion control techniques that will substantially change current state-of-the-art boiler designs[10] have been proposed.

The present study was directed toward an assessment of the effect of coal properties on the fate of fuel-bound nitrogen under both fuel-lean and fuel-rich combustion conditions. A total of 21 coals from 11 States were burned in a 21 kW refractory-lined tunnel furnace in air or nitrogen-free mixtures as the oxidant. Exhaust and in-flame measurements were made to quantify the influence of coal composition and stoichiometry on the speciation of the fuel nitrogen at the exit of the first stage.

EXPERIMENTAL

Furnace system

Figure 1 presents a schematic of the down-fired 15.2 cm i.d. tunnel furnace used in this study. Pulverized coal was supplied pneumatically from a hopper-fed screw feeder to the pre-mixed burner. Pre-mixing was achieved by direct impingement of the coal jets with the main combustion air supply in a pre-mixing chamber, which was separated from the combustion zone by a series of water-cooled tubes that prevented flashback (see *Figure 1*). The coal–air

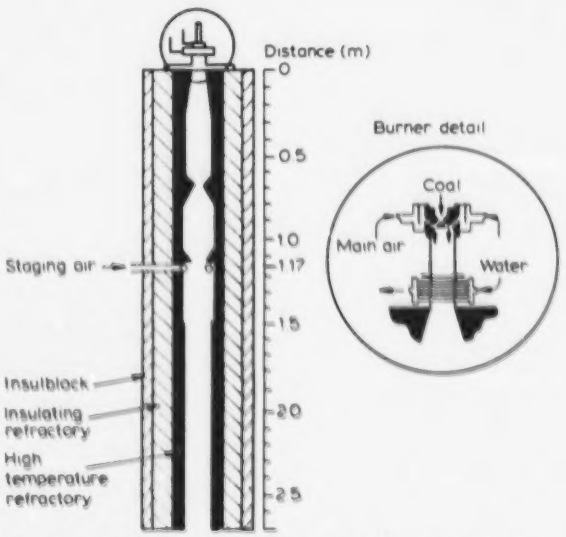

Figure 1 Schematic of down-fired tunnel furnace and burner system

0016 2361/82/121218 07$3.00

Table 1 Fuel analysis

Fuel symbol	▽	◈	□	○	◇	△	▽	◇	○	◺	⊘
Fuel source	Hazellon PA	Upper Cliff AL	Rosa AL	Black Creek AL	W. Ky	WV	Elkay WV	Gauley WV	Price UT	Price UT	UT
Proximate analysis (wt % as received)											
Moisture	5.1	3.0	8.0	2.2	5.4	7.6	0.6	3.7	6.4	7.4	4.2
Ash	5.7	9.5	6.8	4.4	7.5	12.0	11.6	26.9	7.4	8.8	9.6
Volatile matter	4.4	20.4	21.8	28.3	37.8	29.1	33.4	26.7	38.9	38.8	43.0
Fixed carbon	84.7	67.1	63.4	65.0	49.3	51.3	54.4	42.7	47.3	44.9	43.2
Ultimate analysis (wt % dry)											
C	88.4	79.3	81.2	82.1	71.6	74.7	74.0	59.4	73.2	72.2	69.4
H	2.1	4.5	4.7	5.2	5.4	5.0	4.9	4.1	5.5	5.7	5.3
N	0.8	1.5	1.5	1.8	1.5	1.4	1.4	1.4	1.5	1.5	1.5
S	0.5	1.2	1.0	0.8	3.2	0.9	2.5	0.8	0.7	0.8	1.0
Ash	6.1	9.8	7.38	4.6	8.0	13.0	11.7	27.9	7.9	9.5	10.1
O	2.1	3.7	4.08	5.6	10.3	5.1	5.6	6.3	11.2	10.2	12.7
Heating value (kJ g^{-1}, wet)	30.50	30.85	31.15	33.20	28.10	28.45	30.50	23.50	28.70	27.65	27.25
Classification (ASTM D388)	Anthracite	Medium Volatile Bituminous	Medium Volatile Bituminous	Medium Volatile Bituminous	High Volatile A Bituminous	High Volatile A Bituminous	High Volatile A Bituminous	High Volatile A Bituminous	High Volatile B Bituminous	High Volatile B Bituminous	High Volatile B Bituminous

Fuel symbol	□	◈	▽	◇	◥	◱	◊	○	□	△
Fuel source	Cadiz OH	Four Corners NM	Colstrip MT	Hardin MT	Hardin MT	TX	Scranton ND	Beulah ND	Beulah ND	Savage MT
Proximate analysis (wt % as received)										
Moisture	4.3	5.2	21.3	22.8	20.5	25.2	35.0	33.1	34.6	36.4
Ash	18.1	24.1	9.6	11.3	8.6	10.3	7.5	7.1	5.0	4.6
Volatile matter	34.9	36.0	30.8	31.3	33.2	35.3	28.8	28.7	27.0	28.5
Fixed carbon	42.8	34.8	38.3	34.9	37.7	29.2	28.7	31.1	33.4	30.5
Ultimate analysis (wt % dry)										
C	62.1	56.0	67.5	65.5	67.9	61.0	64.6	65.3	66.1	65.0
H	4.4	4.7	4.4	4.1	4.6	4.5	4.2	4.0	4.2	4.0
N	1.1	1.2	1.4	1.0	1.0	1.1	0.8	1.0	1.0	1.0
S	7.4	1.0	0.6	0.8	1.1	1.0	1.5	1.1	0.4	0.4
Ash	18.9	25.4	12.2	14.6	10.8	13.7	11.5	10.6	7.6	7.2
O	6.1	11.6	13.9	14.0	14.6	18.6	17.3	18.0	20.7	22.3
Heating value (kJ g^{-1}, wet)	25.65	21.90	21.35	20.00	21.45	18.90	15.00	16.85	16.85	16.25
Classification (ASTM D388)	High Volatile B Bituminous	High Volatile C Bituminous	Sub-Bituminous B	Sub-Bituminous B	Sub-Bituminous B	Sub-Bituminous C	Lignite A	Lignite A	Lignite A	Lignite A

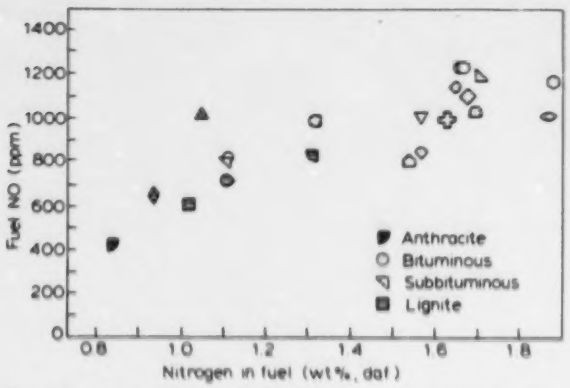

Figure 2 Fuel NO (0% O_2, dry) as a function of Nitrogen Content (21 kW, 5% O_2 in stack). See *Table 1* for symbols

mixture burned in a plug-flow mode with the ignition zone situated in the refractory burner quarl.

All of the excess-air screening experiments were carried out with the straight tunnel configuration that has been described in detail elsewhere[11]. Prior to the staging studies the furnace was modified to facilitate the measurement of in-flame species concentrations. The modified furnace, as illustrated in *Figure 1*, included a refractory staging choke to isolate the first stage and a removable radial-air ring for second-stage air injection.

Analytical methods

Exhaust samples were withdrawn with a stainless steel water-jacket probe and analysed using standard continuous instrumentation (chemi-luminescent NO, paramagnetic O_2, and NDIR CO and CO_2). NO_2 was not measured. A water-spray probe was used for taking in-flame samples[11].

Gas-phase HCN and NH_3 species were collected in a gas-washing unit that consisted of an impinger in series with a bubbler containing a fritted glass cylinder. The sample solutions were subsequently analysed for CN^- and dissolved ammonia using specific-ion electrodes. A lead carbonate–sodium carbonate solution was used in both the impinger and the bubbler to remove sulphide ions. The probe and analysis systems were validated by sampling gases of known composition.

Solid samples were withdrawn isokinetically from the combustion zone with a water-spray probe. Their ultimate composition was determined with a Perkin-Elmer 240 B Elemental Analyzer.

Fuels

Table 1 gives the compositions of the 21 coals used in this study. They ranged from anthracite through lignite and were all pulverized to approximately 65 ± 8 wt% < 75 μm (passing 200 US mesh). The proximate analysis data are presented on an as-burned basis. The coals were not pre-dried during pulverization or prior to the testing.

RESULTS

Fuel-lean conditions

Figure 2 shows fuel NO emissions as a function of wt% (N) in the original coal (daf) for 22 different coals ranging from anthracite to lignite. These data were obtained with the pre-mix burner in the unmodified tunnel furnace at a nominal firing rate of 21 kW (approximately 2.27 kg hr^{-1} (coal)) with 5 vol% excess O_2 and preheating of combustion air to 260 C. Fuel NO was defined as the emission when molecular nitrogen was excluded from the oxidant and the fuel was burned in a 21 vol% oxygen, 18 vol% CO_2 and 61 vol% argon.

In general, fuel NO emissions increased with increasing fuel nitrogen contant. Low-rank coals usually contained less nitrogen and produced less NO than the high volatile bituminous coals; however, within any rank other properties had a significant impact on fuel nitrogen oxidation. For example, the Savage and Beulash lignites both contained approximately 1.05 wt% N, yet their emissions differed by more than 60%. Likewise, the Utah and West Virginia high-volatile bituminous coal emissions varied in the range 800–1250 ppm NO.

The variation in emissions at constant total nitrogen is in marked contrast to previously reported data on gaseous and liquid fuels[12] and is believed to be related to volatile nitrogen reactivity. The low-volatile (4 wt%) Pennsylvania anthracite produced relatively less fuel NO than did the high-volatile (40 wt%) Utah coals. However, attempts to quantify this secondary dependence in terms of the standard ASTM composition parameters (e.g., wt% volatiles, wt% hydrogen, wt% oxygen, coal rank) proved unsuccessful. Determination of volatile nitrogen evolution was also inadequate; the data do not correlate with the total nitrogen evolved in the ASTM volatile test (as measured by analysis of the residual char).

Gay *et al.*[13] attempted to define the volatile, *reactive* nitrogen content of six of the most varied coals from this study by pyrolysing them under inert conditions at 1100 C and then measuring the volatile nitrogen species which were convertible to HCN. *Figure 3* shows that the data from pyrolysis experiments carried out in a quartz reactor agree qualitatively with the experimental results obtained in this study. The Savage lignite has the highest conversion of fuel nitrogen to NO in the combustion experiment and also the highest fractional volatile reactive-nitrogen yield in the inert pyrolysis study. Likewise, the Beulah lignite gave the lowest values in both experiments.

Thus, it appears that in rapidly mixed, unstaged combustors high NO emissions can be expected from coals containing large amounts of fuel nitrogen, particularly if that nitrogen evolves at low temperatures in a reactive form.

Fuel-rich conditions

Laboratory, pilot scale and field tests have demonstrated that NO emissions from pulverized coal combustors can be effectively controlled by some type of staged combustion, either aerodynamic or external. Therefore, defining the impact of fuel properties on the optimization of this concept is of considerable practical significance.

Primary zone stoichiometry

Figure 4 summarizes staged combustion results for a variety of fuels with the premixed burner in the modified furnace. Second stage air was injected via the stainless steel air ring after the choke at a distance of 1.17 m from the burner. All of the data were obtained at 5 vol% overall excess O_2.

For all the coals tested except anthracite, NO

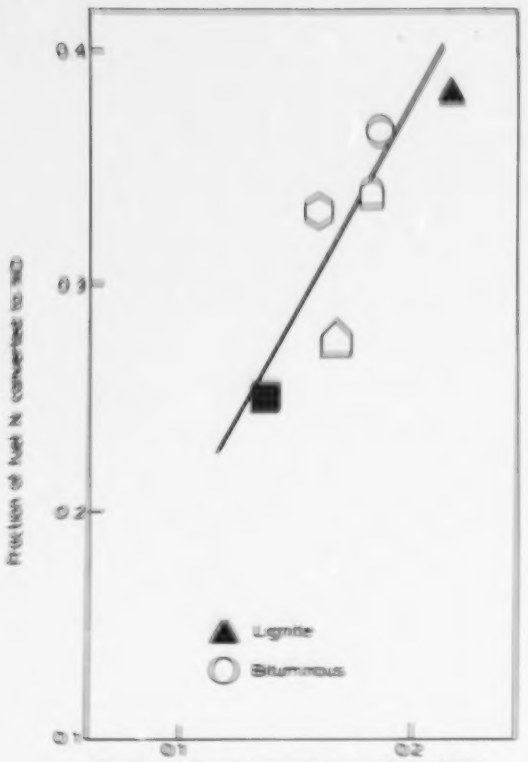

Figure 3 Fractional conversion of fuel nitrogen to NO (5% O_2 in stack) as a function of HCN formed during inert pyrolysis. See *Table 1* for symbols

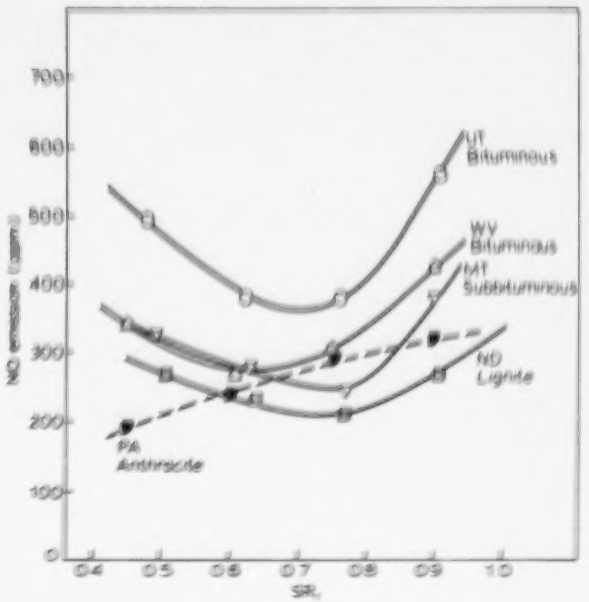

Figure 4 Influence of first stage stoichiometry on exhaust NO (5% O_2, dry) emissions. See *Table 1* for symbols

decreased, reached a minimum, and then subsequently increased as the first stage stoichiometry was progressively reduced. This trend is in agreement with previous results using bituminous coal[14,15]. However, anthracite (and a Utah coal char, not shown) did not exhibit this minimum. Further, both the optimum stoichiometric ratio (SR) and the NO/SR gradient were dependent on the fuel composition.

In-flame measurements of local gas-species concentrations, were made for 12 coals to define the relationship between coal composition and first-stage parameters. Solids composition and particle temperature were also determined in a limited number of cases. Figure 5 shows a set of typical results for the Beulah, North Dakota, lignite with the pre-mixed burner. All gas-phase concentration measurements are shown on an as-measured (dry) basis, except the exhaust NO concentrations, which have been reduced to 0 vol% O_2 (SR = 1.0, based on measured exhaust O_2 concentrations). As the first-stage stoichiometry was reduced, the NO leaving the first stage decreased, but ultimately this was compensated for by an increase in other oxidizable nitrogen species (e.g., HCN and NH_3). This behaviour is analogous to that reported by Takagi et al.[16] for CH_4–NH_3 flames.

Particle temperatures were measured at 0.53 m using two-colour pyrometry[17]. Wavelengths of 750 mm and 950 mm were used in this study and the technique was estimated to be accurate to ±50K. Particle temperatures decreased with decreasing SR. Significant amounts of the initial nitrogen and carbon remained in the solid phase and were carried into the second-stage flame below

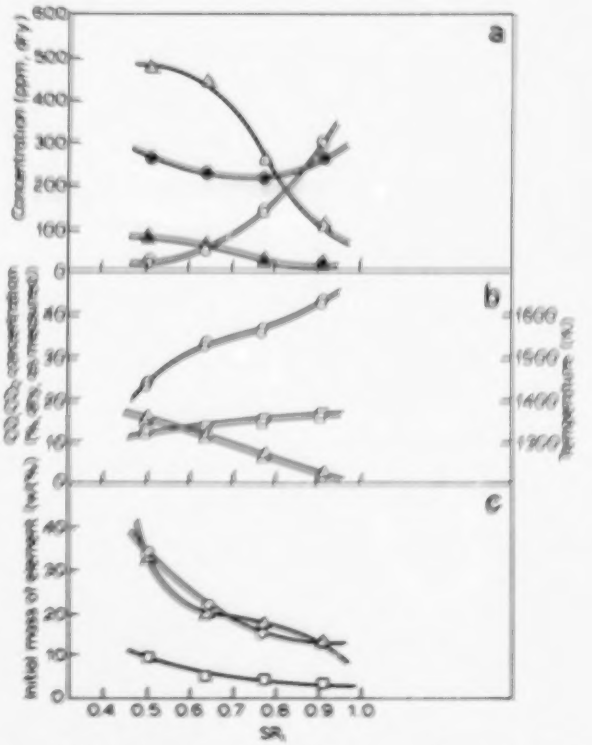

Figure 5 First stage effluent conditions for Beulah, North Dakota lignite with the premixed burner. (a): ●, Stack NO (0% O_2) staged at approx. 1.1 m (SR = 1.25); ○, NO at approx. 1.17 m; ▲, HCN at approx. 1.17 m; △, NH_3 at 1.17 m. (b): ○, Particle temperature at approx. 0.53 m; □, CO_2 concentration at approx. 1.17 m; △, CO concentration at approx. 1.17 m. (c): ○, C; △, N; □, H at approx. 1.17 m

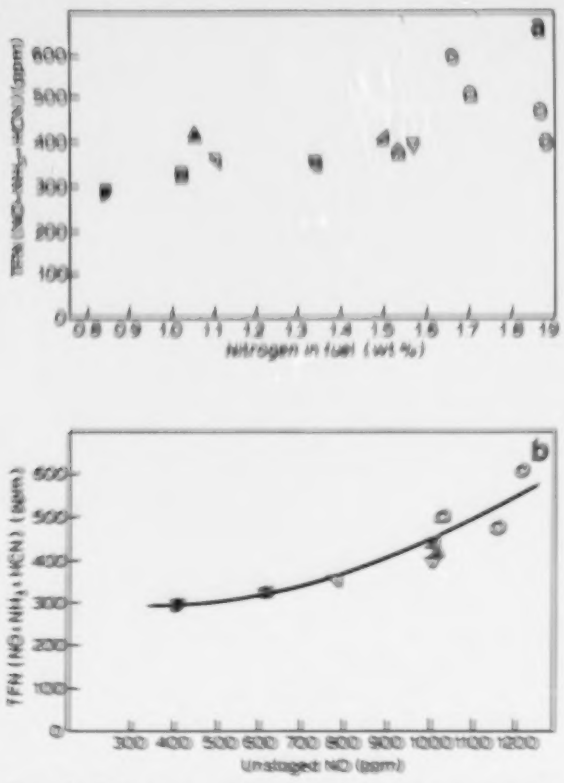

Figure 6 TFN content as a function of (a) coal nitrogen content; and (b) unstaged NO emissions. See *Table 1* for symbols

stoichiometric ratios of 0.7. Thus, there exists a minimum in exhaust NO concentrations because of the competition between decreased first-stage NO and increased oxidizable gas- and solid-phase nitrogen species.

Fuel composition

Figure 6 summarizes the total *gas-phase* fixed nitrogen ($TFN = NO + NH_3 + HCN$) measurements for the 12 coals tested. These data were obtained at a distance of 1.17 m, and a primary-zone stoichiometry of 0.75 with the pre-mixed burner. In general, TFN increased with increasing fuel nitrogen content in the coal (*Figure 6a*); however, within any rank and nitrogen content there were significant other fuel effects. Total fixed nitrogen (TFN) correlated well with the exhaust NO emissions measured under unstaged (excess air) conditions (*Figure 6b*). Coals that had high emissions under excess air conditions produced large amounts of gas-phase nitrogen species under fuel-rich conditions (e.g., the Utah bituminous coal). The low-volatile Pennsylvania anthracite gave very low emissions under excess air operation and produced little TFN under fuel-rich conditions.

Figures 7 and *8* summarize the influence of coal composition on the partition of the gas phase nitrogen species. All of the data are plotted on a cumulative ($NO + HCN + NH_3$) basis and have been corrected to 0 vol% O_2, dry. (The influence of H_2 on the total flue gas volume was neglected.)

Figure 7 shows the NO, HCN and NH_3 measurements for the Pennsylvania anthracite and three bituminous coals with equal nitrogen contents (1.63 ± 0.04 wt%, daf).

The anthracite produced essentially no HCN or NH_3; at all stoichiometries the dominant TFN species leaving the first stage was NO. In addition, the anthracite produced a relatively large amount of first stage NO; at $SR_1 = 0.7$, first stage NO accounted for 17.5 wt% of the anthracite fuel nitrogen, but only 6–11 wt% of the fuel nitrogen in the bituminous coals tested. The increased first stage NO with the anthracite (and coal chars, not shown) may be due to an increased oxygen partial pressure in the early stages of the combustion. With low volatile fuels the rate of O_2 consumption is reduced due to decreased hydrocarbon evolution.

With all four of the bituminous coals, first stage HCN concentrations exceeded NH_3 at all stoichiometries tested. Further, both NH_3 and HCN usually increased with increasing fuel volatility. *Figure 7* shows data ranging from a medium volatile bituminous (Ross, Alabama, 21.8 wt% volatile matter) to a high volatile B bituminous (Price, Utah, 38.9 wt% volatile matter). This increase in reactive-gas-phase nitrogen was accompanied by a smaller percentage reduction in the nitrogen retained in the solid phase at the end of the first stage.

Figure 8 shows typical results for a subbituminous coal (Hardin, Montana) and two lignite coals (Beulah, North

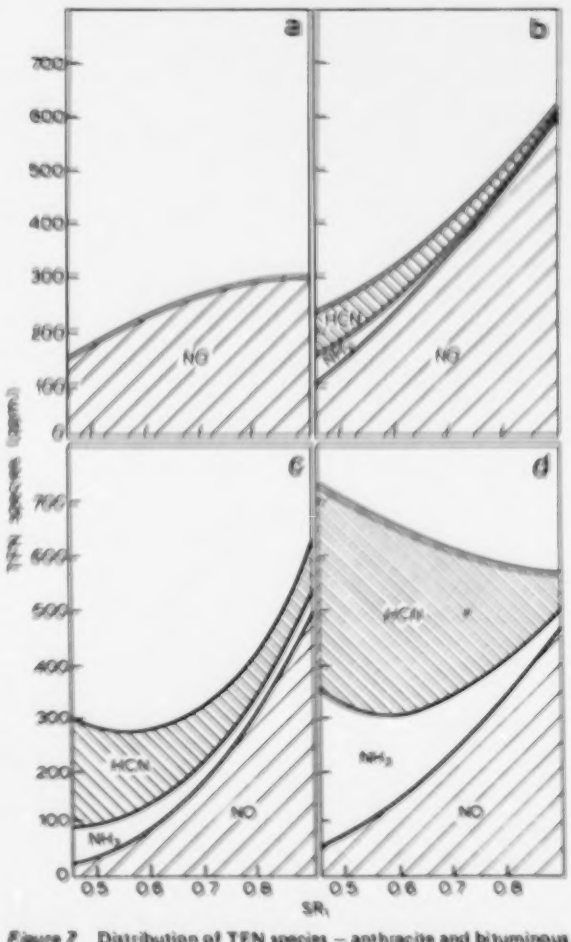

Figure 7 Distribution of TFN species – anthracite and bituminous coals (a) PA anthracite; (b) Ross AL medium volatile bituminous; (c) WV high volatile a bituminous; (d) UT high volatile B bituminous

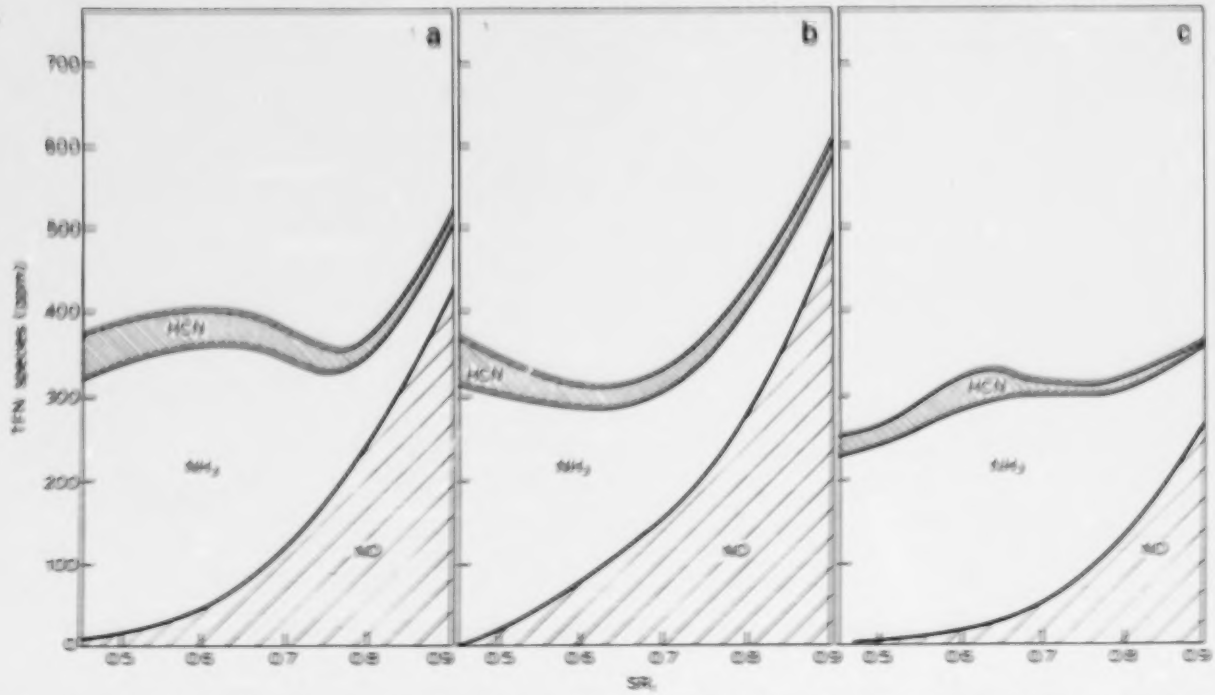

Figure 8 Distribution of TFN species — subbituminous and lignite coals: (a) Hardin MT subbituminous B; (b) Savage MT lignite A; (c) Beulah ND lignite A

Dakota, and Savage, Montana). All five of the lower rank coals tested had high NH_3 concentrations at the end of the first stage. For example, at $SR_1 = 0.7$ approximately 10 wt% of the initial fuel nitrogen left the first stage as NH_3 with the lower rank coals. NH_3 was less than 4 wt% for all of the bituminous coals.

First stage HCN concentrations were significantly less than NH_3 levels at all stoichiometries for all subbituminous and lignite coals. NO concentrations at the first stage outlet were also low relative to the anthracite and bituminous results. In general, NO appears to decrease consistently with decreasing rank from anthracite to lignite.

The increased importance of HCN in the bituminous coals may be directly linked to the initial coal structure. Solomon and co-workers[10,19] have found that high rank coals retain their nitrogen more strongly than lignites. Bituminous coals also produce large amounts of aliphatic hydrocarbons, while lignites produce more CO.

ACKNOWLEDGMENTS

This work was supported by EPA Contract 68-02-2667. The authors are happy to acknowledge the contribution of their colleagues in the conduct of the experiments, particularly W. R. Seeker for his help with particle temperature measurement and also the encouragement and ideas resulting from discussions with A. Axworthy, A. F. Sarofim and P. Solomon.

REFERENCES

1 Heap, M. P., Lowes, T. M. and Walmsley, R. *Fourteenth Symp. (Internat.) Combustion*, The Combustion Institute, Pittsburgh, PA 1973, p. 883

2 Pershing, D. W. and Wendt, J. O. L. *Sixteenth Symp. (International) on Combustion*, The Combustion Institute, Pittsburgh, PA 1977, p. 389

3 Pohl, J. H. and Sarofim, A. F. *Sixteenth Symp. (International) on Combustion*, The Combustion Institute, Pittsburgh, PA 1977, p. 491

4 Solomon, P. R. and Colket, M. B. *Seventeenth Symp. (International) on Combustion*, The Combustion Institute, Pittsburgh, PA 1979, p. 131

5 Wendt, J. O. L., Pershing, D. W., Lee, J. W. and Glass, J. W. *Seventeenth Symp. (International) on Combustion*, The Combustion Institute, Pittsburgh, PA 1979, p. 77

6 Rees, D. P., Sawyer, L. D. and Hedman, P. O. *Eighteenth Symp. (International) on Combustion*, The Combustion Institute, Pittsburgh, PA 1980, p. 000

7 Baron, J. A. 'Pulverized coal firing NO$_x$ control', *Proc. of Second NO$_x$ Control Technol. Sem.*, Electric Power Research Institute, 1978

8 Vatsky, J. 'Experience in reducing NO$_x$ emissions in operating steam generators', *Proc. of Second NO$_x$ Control Technol. Sem.*, Electric Power Research Institute, July 1979

9 Zallen, D. M., Gershman, R., Heap, M. P. and Nuruzzaman, W. H. *Proc. Third Stationary Source Combustion Symp.*, Feb. 1979, 2, p. 73

10 Johnson, S. A., Ciolli, P. L., Sommer, T. M. and McElroy, M. W. 'Primary combustion furnace system, an advanced low NO$_x$ concept for pulverized coal combustion', *Proc. of Second NO$_x$ Control Technol. Sem.*, Electric Power Research Institute, 1978

11 Chen, S. L., Heap, M. P., Pershing, D. W., Nihart, R. K. and Rees, D. P. 'Influence of fuel composition on the formation and control of NO$_x$ in pulverized coal flames', Western States Section, Combustion Institute, Spring Meeting, Irvine, CA, April 1980

12 England, G. C., Heap, M. P., Pershing, D. W., Nihart, R. K. and Martin, G. B. *Eighteenth Symp. (International) on Combustion*, Pittsburgh, PA 1980

13 Gay, R. L., Axworthy, A. E., Dayan, V. H. and Recht, H. L. 'Volatility of fuel nitrogen', EPA Fundamental Combustion Research Contractors Review Meeting, Newport Beach, CA, January 1980

14 Altenkirch, R. A., Peck, R. E. and Chen, S. L. *Combustion Sci.*

Technol. 1979, **20**, 49
15 Brown, R. A., Mason, H. B., Pershing, D. W. and Wendt, J. O. L. 'Investigation of first- and second-stage variables on control of NO_x emissions in a pulverized coal furnace', 83rd National Meeting, AIChE, Houston, TX, March 1977
16 Takagi, T., Tatsumi, T. and Ogasawara, M. *Combustion Flame* 1979, **35**, 17
17 Seeker, W. R., Samuelsen, G. S., Heap, M. P. and Trolinger, J. D. *Eighteenth Symp. (International) on Combustion*, Pittsburgh, PA 1980
18 Solomon, P. R. and Colket, M. B. *Fuel* 1978, **57**, 749
19 Solomon, P. R. 'In analysis of coal and coal volatiles', EPA Fundamental Combustion Research Contractors Review Meeting, Newport Beach, CA, January 1980